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SCORPIO AT THE 6-M TELESCOPE: CURRENT STATE AND PERSPECTIVES FOR SPECTROSCOPY OF GALACTIC AND EXTRAGALACTIC OBJECTS

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Abstract. A significant part of observations by Russian 6-m telescope is carried out using SCORPIO multi-mode focal reducer. A lot of scientific data have been collected using observations in direct imaging, slit spectroscopy and Fabry-Pérot interferometry modes during the past ten years. Some results of these observations are considered in this review. We are also present a short description of a new generation instrument named SCORPIO-2.

Key words: Instrumentation: spectrograph – Instrumentation: polarimeters – ISM: kinematics and dynamics – Galaxies: active

1. INTRODUCTION

In the middle of the last century Georg Courtés (1960) suggested and realized the idea of a focal reducer. In addition to increasing the field-of-view of a large optical telescope and correction of the off-axis primary mirror aberration, a focal reducer makes it possible to have a multi-mode instrument, because it becomes possible to install dispersing elements in a output pupil between the collimator and the camera, which turns the direct imaging system into an universal spectrograph. The first prototype of the device designed for spectroscopy and photometry of faint extended objects was an EFOSC camera at the 3.6-m ESO telescope (Buzzoni et al. 1984). Now a lot of multimode low-resolution spectrographs are used at middle-size and large telescopes. SCORPIO (Spectra Camera with Optical Reducer for Photometric and Interferometric Observations) have worked at the primary focus of the 6-m SAO RAS telescopes since Sep. 2000. In the paper by Afanasiev & Moiseev (2005) we gave a short description o the device, while technical details are considered in Afanasiev et al. (2005). See also current information presented on the SCORPIO web-page (see the footnote below). Today it is the most frequently used facility, that has been employed half of observation time at the 6-m telescope (Figure 1). In this review we consider briefly some scientific results obtained with the use of SCORPIO and also our current work to modify and improve of a technique of a faint object spectroscopy by the SAO RAS telescope.

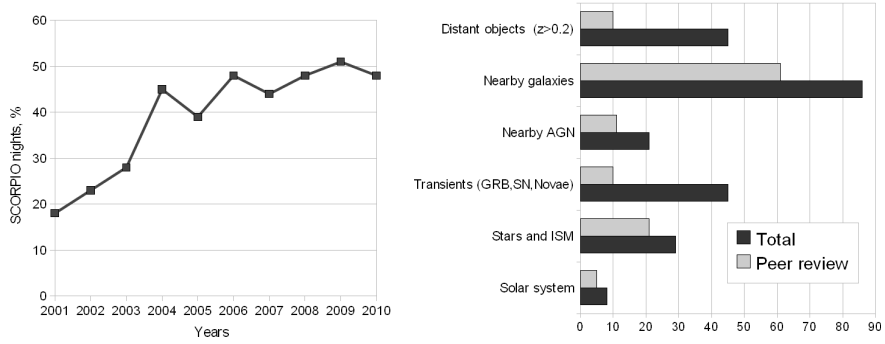

Fig. 1. The percentage of the calendar time distributed by 6-m telescope Program Committee for SCORPIO observations (left). Distribution of publications based on SCORPIO observations in 2001-2011 between different topics (right): the total amount (black) and in peer-review journals only (gray).

2. SCORPIO OBSERVING MODES

The multimode focal reducer allows various spectroscopic and photometric observations to be performed within 6 arcmin field-of-view (see, Figure 2). The list of observing modes is as follows.

- Direct imaging in broad-band $UBVR_CI_C$ filters; medium- and narrow-band interferometric filters.
- Long-slit spectroscopy with volume phase holographic gratings (VPHGs).
- Slitless spectroscopy for observations of spectrophotometric standard stars.
- Multi-slit unit for spectroscopy with 16 movable slits (18″ in each height).
- Spectropolarimetry using the analyzer based on a Savar plate (see Afanasiev & Moiseev (2005) for details of the data analysis).
- 3D spectroscopy with a scanning Fabry-Pérot interferometer (FPI). The realization of this technique in SCORPIO as well as a data reduction are described in Moiseev et al. (2002) and in Moiseev & Egorov (2008)

We can change the modes during the same night of observation, however some restrictions exist, for instance, it is impossible to switch between long-slit and multi-slit modes. The quick switch between the main modes (long-slit/imaging, FPI/imaging, etc.) allows an observer to choose targets that match best the current atmospheric conditions (i.e. seeing and transparency). That is very important in case of unstable weather around the 6-m telescope site.

3. SCIENTIFIC RESULTS

According to the ADS database for the 2001 to June 2011 period, the data obtained with SCORPIO were presented in 215 publications, including peer-review articles, conference proceedings, telegrams, etc[1]. They have been cited more than

[1]The updated list of publications is available at the SCORPIO web-page: `http://www.sao.ru/hq/lsfvo/devices/scorpio/scorpio.html`

1000 times. Results of these observations were used in more than fifteen Ph.D. theses. Figure 1 (right) shows the distribution of these publication between different astrophysics topics, which reflects the main interest of the astronomers who requested observing time with SCORPIO. *It would be quite impossible in a short paper to give a full review of all published results. Therefore, below we will consider only certain works selected according to our preferences in order to show a large range of tasks and methods.*

3.1. Solar System

The activity of a number of distant comets was investigated using the photometric and spectroscopic observations with SCORPIO – see, for instance, Korsun et al. (2008, 2010). The origin of the activity at the distance larger than 5 AU is a puzzle, however, molecular emissions were found in some objects. For example, in C/2002 VQ94 (LINEAR) emission bands of CO^+ and N_2^+ were detected at a record heliocentric distance – 7.3 AU. It is an evidence of the fact that they had been formed in the outer regions of the Solar System or in a pre-solar interstellar cloud in a low temperature ($T < 25$ K) environment.

An interesting result was obtained by Afanasiev et al. (2007) who recorded the spectrum of a faint meteor during the observations of the spectra of galaxies with the multi-slit unit. The velocity of the entry of the meteor body into the Earth's atmosphere estimated from the emission lines line-of-sight velocity is about 300 km/s. Based on this results authors supposed that this meteor particle is likely to be of an extragalactic origin.

3.2. Stars and Interstellar Medium

Thanks to high optics transparence and the large diameter of the telescope mirror, SCORPIO is widely used for snapshot and monitoring observations of faint transient objects in the frameworks of several programmes with aims to study spectral evolution of Novae (see for instance, Fabrika et al. 2009) and Supernovae stars, including distant core-collapse SNe probably associated with gamma-ray bursts (Moskivitin et al. 2010). SCORPIO data provide a spectral confirmation for newly discovered massive evolved stars (WR, LBV) in our Galaxy (Gvaramadze et al. 2009) and other nearby galaxies: M33 (Valeev et al. 2009) and DDO68. In the latter case Pustilnik et al. (2008) have discovered a luminous blue variable from the transient event in the spectra of HII region of DDO68.

Observations with a scanning FPI makes it possible to study the structure of desired spectral lines (Hα, [O III], [SII]) simultaneously in a large (6 arcmin) field-of-view. It provides rich opportunities for investigating the emission-line kinematics of the ionized gas in interplay between stars and the surrounding medium. The examples in our Galaxy are the study of jets and emission knots ejected from young stellar objects (Movsessian et al. 2007, 2009), kinematics of bow shock fronts in pulsar-wind nebula CTB 80 (Lozinskaya et al. 2005), and supersonic motions optical filament in the radio nebula W50 around the microquasar SS433 (Abolmasov et al. 2010). The related object – a nebular complex associated with the ultraluminous X-ray sources in the dwarf galaxy HoIX was also studied with the SCORPIO/FPI (Abolmasov & Moiseev 2008). Based on the SCORPIO long-slit and FPI data Lozinskaya & Moiseev (2007) have presented evidences that an explosion of a very massive star (Hypernova) seems to be a more plausible mechanism of formation of the synchrotron superbubble in IC10 galaxy compared

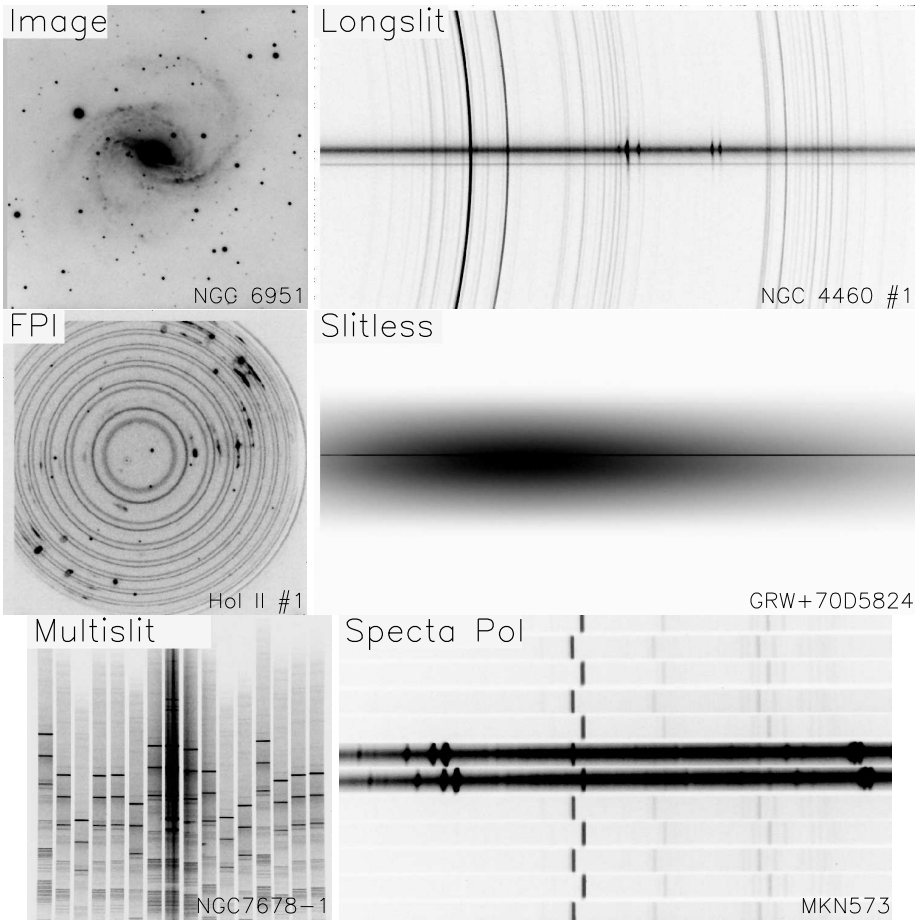

Fig. 2. Examples of data frames for different SCORPIO modes

with the earlier proposed model of multiple supernova explosions. This work is a part of a series of papers aimed at investigating the kinematics of shells and bubbles around star formation regions in nearby dwarf galaxies. A good illustration is the IC1613 galaxy where Lozinskaya et al. (2003) have estimated the expansion velocities of multiple gaseous shells using spatial-resolved kinematic data for ionized (Hα, SCORPIO/FPI) and neutral (21 cm, VLA) interstellar medium.

3.3. Nearby Galaxies

Figure 1 shows that most of SCORPIO publications are related to nearby galaxies. The Hα images for a significant part of all galaxies in the Local Volume (within 10 Mpc) were obtained during a general imaging survey with SCORPIO. Measured Hα fluxes were used to derive the total star formation rate density in the Local Universe – $0.019 \pm 0.003\, M_{\odot}\, yr^{-1}\, Mpc^{-3}$ (Karachentsev & Kaisin 2010). The SCORPIO long-slit spectra were used to study the stellar population in two dE/dSph members of the nearby M81 group of galaxies (Makarova et al. 2010),

whereas Chilingarian et al. (2009) used the multi-slit unit for the following-up spectroscopy of new discovered compact elliptical galaxies in order to investigate their origin and stellar population properties.

Above we already discussed the ionized gas properties in the nearby dwarf galaxies. Using the SCORPIO/FPI observations Martínez-Delgado et al. (2007) have mapped the regions of supersonic gas motions in more distant blue compact galaxies. They offered kinematic diagnostic diagrams that provide a possibility to infer from FPI data the magnitude of the star formation activity in galaxies even if they are not spatially resolved. The spectrophotometric observations conducted with the use of SCORPIO allow one to estimate the oxygen abundance in HII regions of extremely metal-deficient galaxies (see Pustilnik et al. (2010) and reference therein). A detailed analysis of ionized gas morphology and kinematics in nine such galaxies shows the important role of recent interactions and mergers in the triggering of their star formation (Moiseev et al. 2010).

The ionized gas velocity fields derived from SCORPIO/FPI data cubes reveal a complex kinematic picture in the disc of spiral galaxies caused by internal (seculiar evolution) and external (merging, gas accretion) effects: inflow steaming motions in bars, polar discs and rings, circumnuclear counter-rotated component (see previous review in Moiseev 2007). FPI kinematic mapping is very helpful in study of structure and dynamics of peculiar galaxies: colliding ring and polar ring galaxies (see references in the review by Moiseev & Bizyaev 2009). Polar rings are an interesting example of peculiar systems that reveal outer rings or discs, rotating in the plane approximately perpendicular to the disc of the main galaxy. The recent progress in the study of polar rings with SCORPIO was presented in the paper by Brosch et al. (2010) who found the most distant kinematically confirmed polar ring ($z = 0.06$). Here an early-type central galaxy is surrounded by a giant (with a diameter of over 48 kpc) ring of young stars and clouds of ionized gas, inclined at a steep angle to the stellar disc. In contrast to this large-scale structures, Moiseev (2010) has described the smallest ($r < 2$ kpc) polar gaseous discs in blue compact dwarf galaxies. The possible formation mechanism for these discs are merging or accretion of external gas clouds with a specific direction of an orbital momentum. It was also suggested by Sil'chenko et al. (2011) who studied the stellar population and kinematics properties in NGC7217 early-type spiral galaxy using SCORPIO long-slit data. A minor merging event is also a most likely origin for the full-size gaseous discs rotating in the opposite direction to the stellar ones in NGC2551 and NGC5631 lenticular galaxies (Sil'chenko et al, 2009).

The SCORPIO advantages in the spectroscopy of regions with a low surface brightness are illustrated in the papers by Zasov et al. (2008) about stellar kinematics of the discs in S0-Sa galaxies and by Baes et al. (2007), where stellar population age and metallicity distributions in the sample of elliptical galaxies were estimated up to distances of 3 effective radii. The main important conclusion of this work is the absence of a single power law for the metallicity gradient that is inconsistent with the origin of the elliptical galaxies by a major merger.

3.4. Nearby AGN

Together with data taken from some other instruments the SCORPIO spectra were involved in long-term monitoring of Hα and Hβ lines variations of the active galactic nucleus of NGC4151 (Shapovalova et al. 2008) and 3C390.3 (Popović et al. 2011). The main aim is a study of their 'central engine' including Broad Line

Region (BLR). The geometry of the BLR of 3C390.3 seems to be very complex, and inflows/outflows may be present, but the disc-like BLR is the dominant emitter.

Recently, Afanasiev et al. (2011) presented the results of spectropolarimetric observations for a sample of 15 active galactic nuclei. The magnetic field strengths and radial distributions in an accretion disc around a supermassive black hole were evaluated within the framework of traditional accretion disc models.

The large-scale environment of active nuclei was also investigated in numerous papers based on the data collected in the FPI mode. Smirnova et al. (2007) presented the analysis of global ionized gas kinematics in the disc of Mrk 533. In this galaxy the non-circular ionized gas motions at the distance of $r < 2.5$ kpc are associated with an outflow triggered by the nuclear radio jet intrusion in an ambient medium. A very complicated combination of the region with different ionization and kinematics properties was found in Mrk 344 (Smirnova & Moiseev 2010). The most unusual feature is a large-scale cavern filled with a low-density ionized gas. This region seems to be the place where the remnants of a disrupted companion have recently penetrated through the gaseous disc of the main galaxy.

3.5. Distant Objects

SCORPIO shows a good advantage in the spectral identification of the extragalactic radio sources in a wide range of optical magnitudes up to $m_r = 23 - 24^m$. See, for example, the classifications, optical identifications and spectral redshifts for the different samples of radio sources presented by Amirkhanyan et al. (2004) and Afanasiev et al. (2003). Some interesting objects were discovered. For instance, Amirkhanyan & Mikhailov (2006) found a very radio-loud QSO at $z = 4.06$. Recently Parijskij et al. (2010) presented the results of spectroscopy of 71 radio galaxies and QSO with steep and ultra-steep spectra.

SCORPIO follow-up spectroscopy makes a significant contribution to the systematic searches for wide separation gravitational lens systems in the framework of CAmbridge Sloan Survey Of Wide ARcs in the skY (CASSOWARY). The most beautiful object (in our view) was the discovery of the Cosmic Horseshoe (CASSOWARY #1) an almost complete Einstein ring of the diameter of $10''$ around a giant luminous red galaxy at the $z = 0.444$ (Belokurov et al. 2007). The source is a star-forming galaxy that has a z =2.379. This gravlens has a large magnification factor $(25 - 35)$ which allows Quider et al. (2009) to study from VLT spectroscopy the metallicity and starformation properties in the source galaxies with the quality that is currently unfeasible for unlensed galaxies at $z \approx 2 - 3$.

4. NEW PERSPECTIVIES

During its ten years of operation the SCORPIO has been repeatedly upgraded and improved. Unfortunately, opportunities for further upgrading have been exhausted. Also, a new optical scheme was necessary for spectral observations with large format CCD detector. Therefore SAO RAS began manufacturing a new multi-mode spectrograph with enhanced capabilities. The main novelty of the SCORPIO-2 versus its with previous version are as follows (see also Table 1):

- The value of off-axis optical aberration are significantly (by half) decreased.
- The device is specially designed to work under remote control from the Institute building (under the mountain where the telescope is sited). The

Table 1. Comparision of the 6-m telescope old and new facilities

	SCORPIO	SCOPIO-2
Detector	EEV 42-40, $2K \times 2K$	E2V 42-90, $2K \times 4.6K$
Direct imaging: Max. filters positions Field-of-view	 10 (in two wheels) 6.1 arcmin	 27 (in three wheels) 6.1 arcmin
Long-slit spectroscopy	set of slits with fixed width $(0.5 - 2'')$; single VPHG position	variable slit width $(0 - 20'')$; wheel with 9 grating holders
FPI	Common carriage with grating holder	independent holder
Multi-slit unit	16 slits in 6×3 arcmin field-of-view	16 slits in 6×4 arcmin field-of-view
Integral-field unit	–	24×24 lenslet, $0.75''$/lens
Polarymetry	Savar plates, rotated in two positions	Single and double Wollaston prisms; apochromatic phase plates $\lambda/2$, $\lambda/4$; rotated analyser

number of exchangable elements installed simultaneously in the device is significantly increased.

- The opportunities for polarimetry (spectra and images) are greatly expanded.

- The new multi-mode focal reducer includes an Integral-field unit (IFU) based on the combination of small lenses with optical fibers. This scheme was offered by Georg Courtés (1982) and it was first implemented in the two generations of the MultiPupil Fibers Spectrographs (MPFS) at the 6-m telescope (Afanasiev et al. 1990, 2001). Now this type of IFUs is widely used in middle- and large-size telescopes. The SCORPIO-2/IFU $18 \times 18''$ field-of view is divided by square lenses array with a scale of $0.75''$ per lens. Behind each lens an optical fibre is located whose other end is packed into two pseudo-slits in the spectrograph entrance.

The first test observations by the 6-m telescope were carried out in June, 2010. Some electronic and mechanical parts (integral-field and multi-slit units) are still under construction. We are confident that the commissioning of SCORPIO-2 will significantly enhance the abilities of the 6-m telescope in the study of different objects in our Galaxy as well as in extragalactic scales.

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